



VERITAS Observations of Supernova Remnants and Pulsar Wind Nebulae in the Fermi Era

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for the VERITAS Collaboration
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Instrument design:

- Four 12-m telescopes, 3.5° FoV
- FLWO, Mt. Hopkins, Az (1268m)
- Fully operational Sept 2007

Performance:

- 3-level trigger (250 Hz rate)
- ~ 800 hrs/yr dark time, ~ 200 hrs/yr moon time
- Energy threshold ~150 GeV (zenith)
- Energy resolution ~ 15-20 %
- Angular resolution ~ 0.1°



7km away

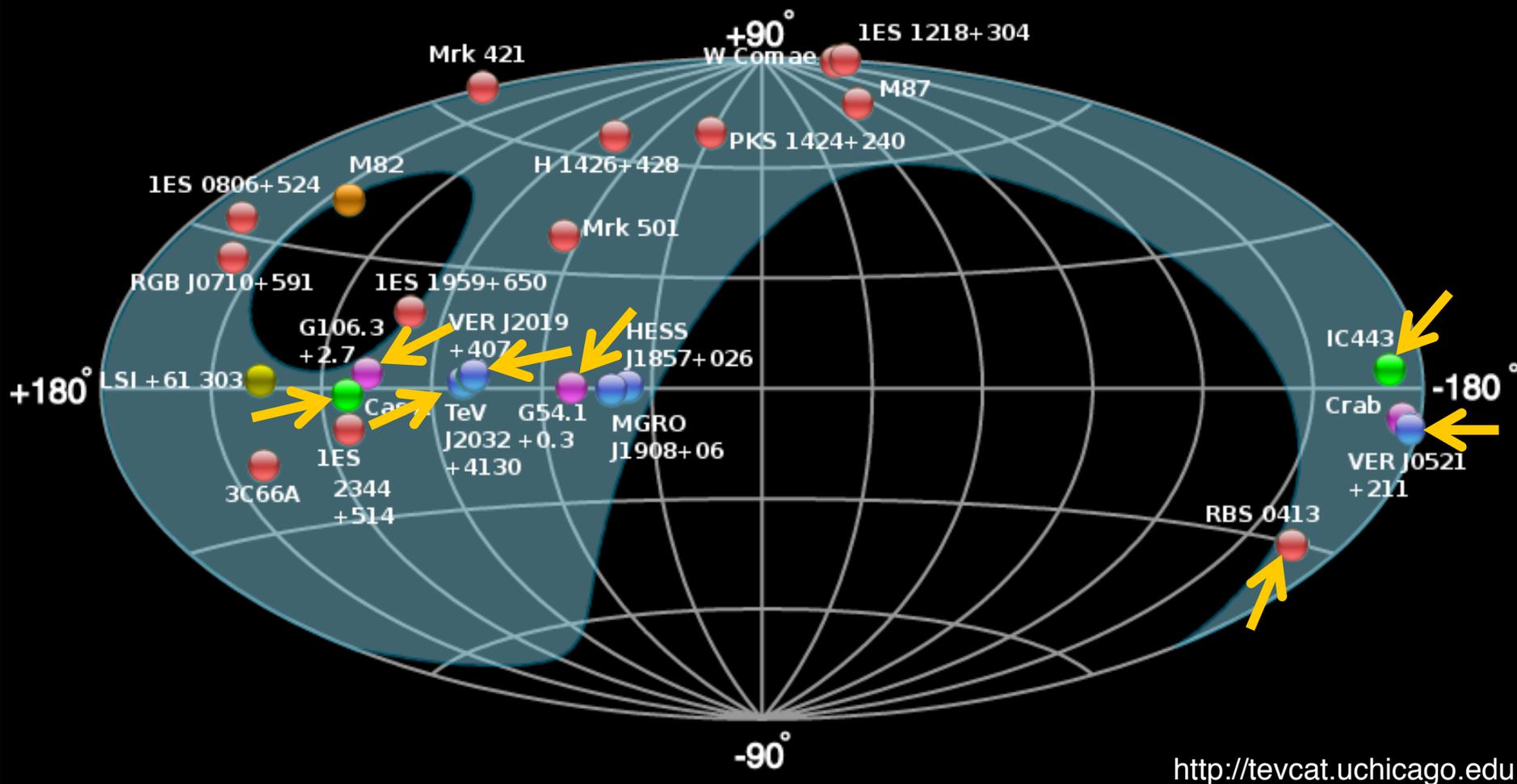


T1
Sep 2009

Sensitivity:

- 1% Crab < 50 hours (before T1 move)
- 1% Crab < 30 hours (after T1 move)
- See poster by J. Perkins *VERITAS T1 Relocation*

The VERITAS VHE Sky



25 Source Detections in 6+ source classes, at least 10 in the Galactic Plane

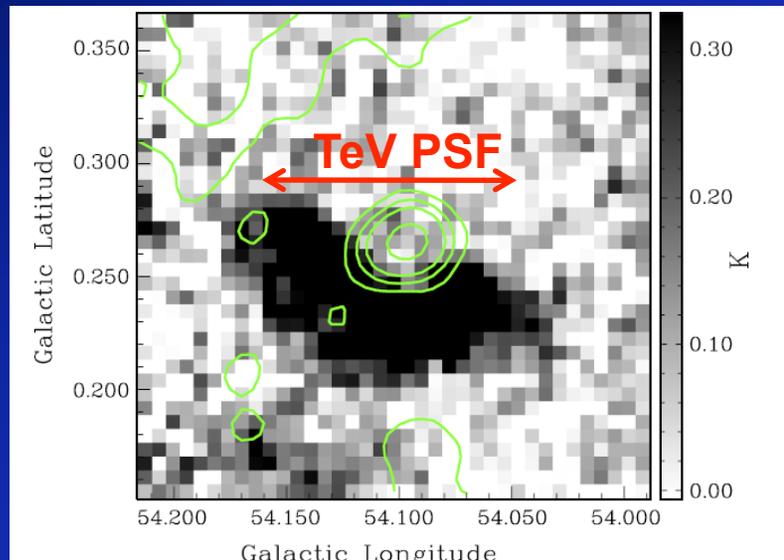
SNR G54.1+0.3 / PSR
J1930+1852

SNR G54.1+0.3 / PSR J1930+1852

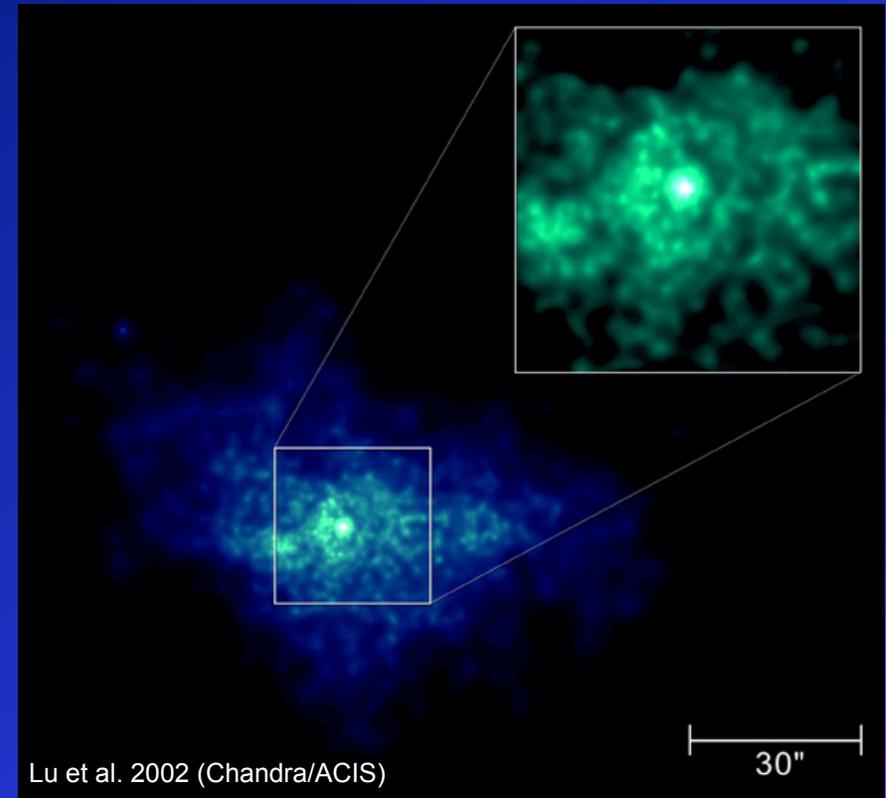


- ▣ “Cousin of the Crab”
 - X-ray jet/torus, no thermal shell
 - Age ~ 2900 years
 - $\dot{E} = 1.2 \times 10^{37}$ erg/s
 - Distance ~ 6.2 kpc

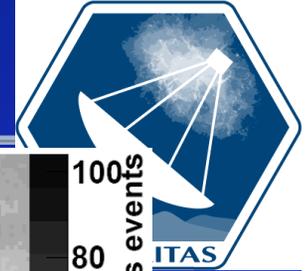
- ▣ Also, Nearby Molecular Cloud:



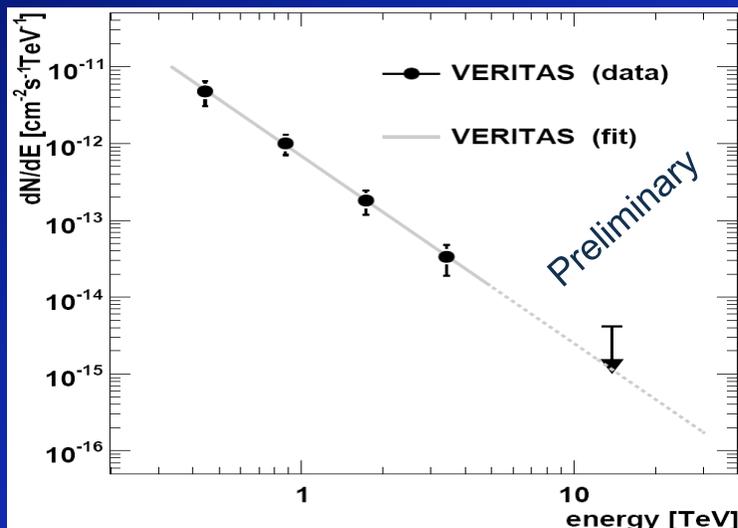
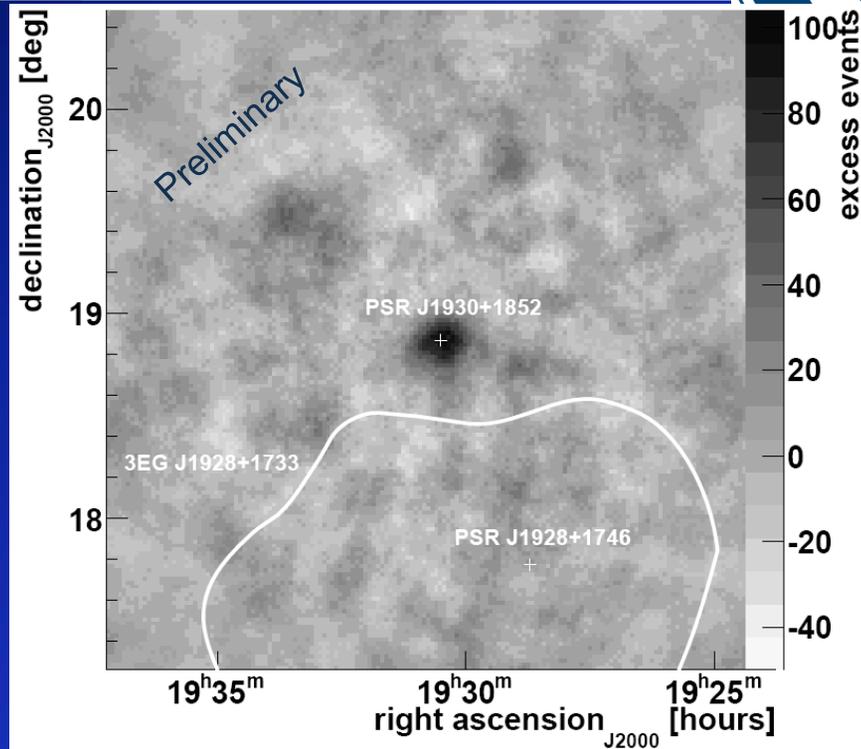
Leahy et al. 2008 (FCRAO)



SNR G54.1+0.3 / PSR J1930+1852



- Hint of signal in 2007 moonlight data.
- 2008 follow-up yields a $7\text{-}\sigma$ detection in 31 hours
- Location compatible with pulsar
- Consistent with point source.
- Power-law spectrum:
 - Index: $2.40 \pm 0.24_{\text{stat}} \pm 0.3_{\text{sys}}$
 - Flux ($> 1 \text{ TeV}$) $\sim 2.5\%$ Crab



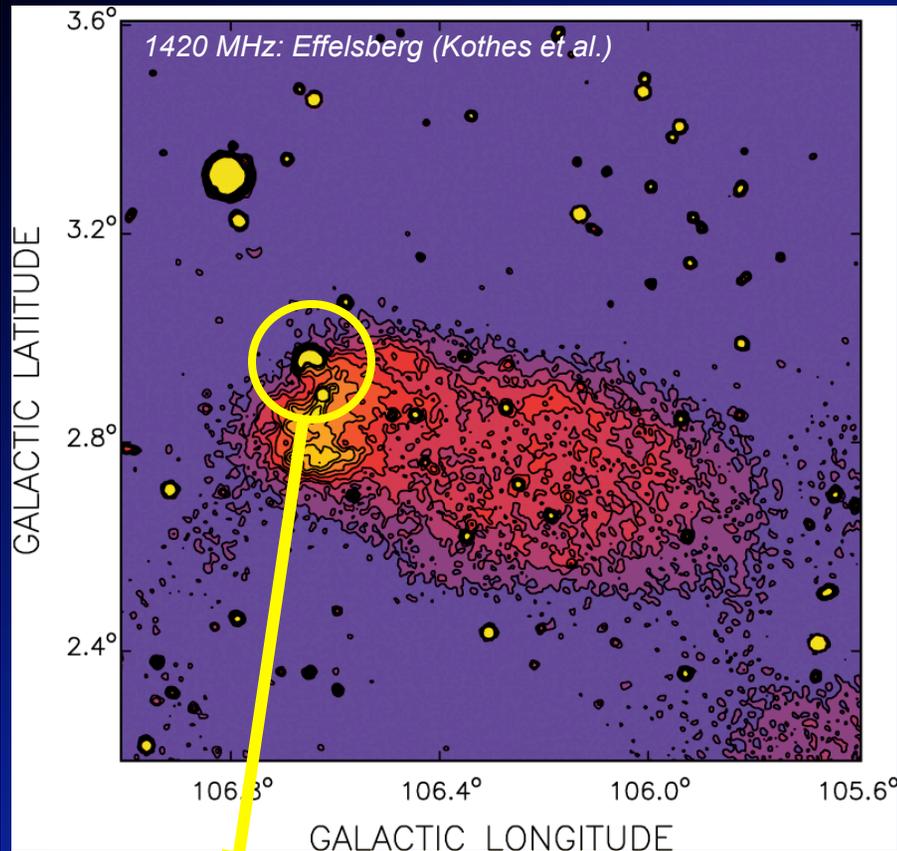
- $L_\gamma / \dot{E} \sim 0.15\%$

- Similar to other young TeV PWNe, eg G0.9+0.1, Kes 75
- VHE γ -rays from freshly injected electrons?
- Enhancement from interaction with

Acciari et al. (2008), in prep. See poster by E. Aliu VERITAS Obs. of PWNe

SNR G106.3+2.7 / PSR
J2229+6114
(aka "Boomerang")

SNR G106.3+2.7 / PSR J2229+6114



- Energetic pulsar + wind nebula discovered in the error box of source 3EG J2227+6122.
 - Age $\sim 10,000$ years
 - $\dot{E} = 2.2 \times 10^{37}$ erg/s
 - Likely part of the larger SNR G106.3+2.7
 - Distance ~ 800 pc (Kothes et al)

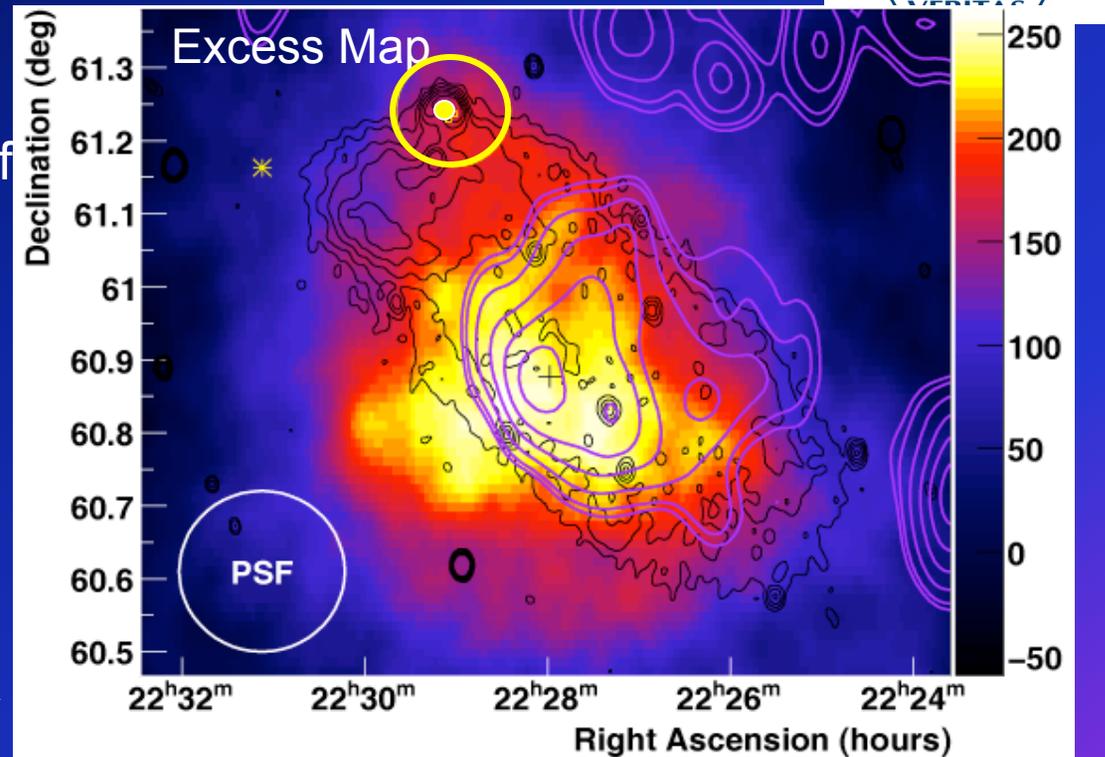
- On Fermi/LAT Bright Source List

- MILAGRO: Extended emission at ~ 35 TeV

SNR G106.3+2.7 / PSR J2229+6114



- ▣ Observations made in 2008 resolve TeV emission overlapping the radio shell of G106.3+2.7
 - 7.3 σ detection in 33 hours (6.0 σ post-trials)
- ▣ TeV emission is extended
 - Spans a $0.4^\circ \times 0.6^\circ$ region
 - Peak is 0.4° away from PSR
 - Overlaps with region of high CO density



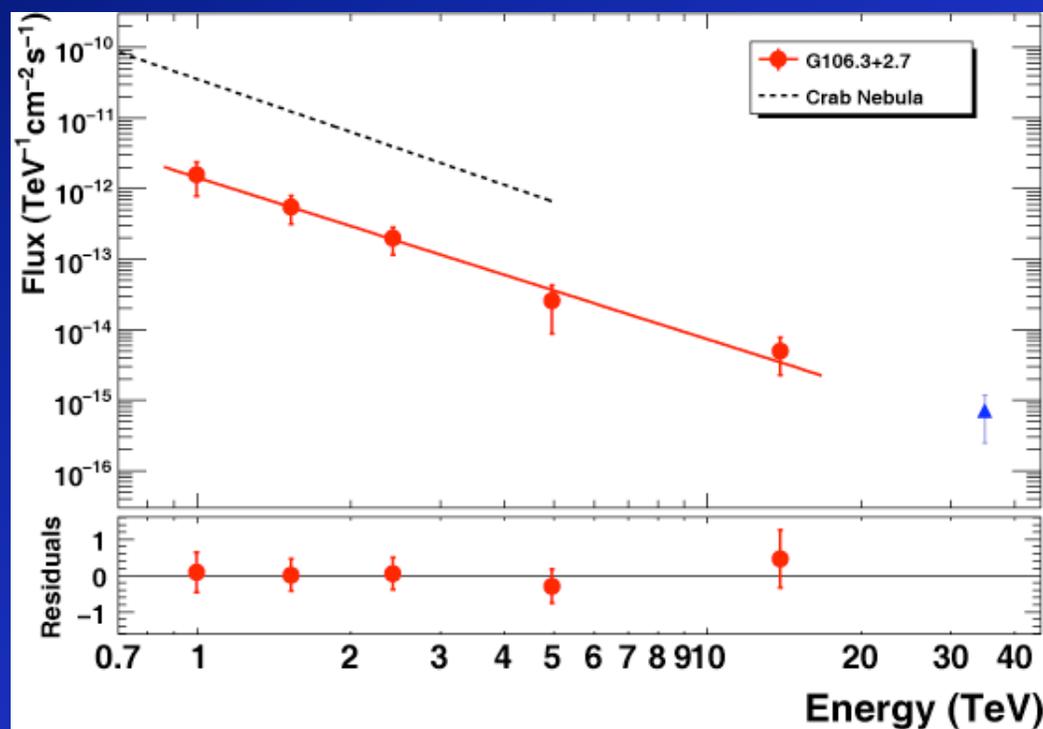
Black – Radio (DRAO)
Circle – FGST Error Box
Dot – Pulsar Position
Purple - ^{12}CO Emission (FCRAO)
Yellow star – 1AGL J2231+6109

Acciari et al. 2009, ApJ 703 L6. See poster by E. Aliu VERITAS Obs. of PWNe

SNR G106.3+2.7 / PSR J2229+6114



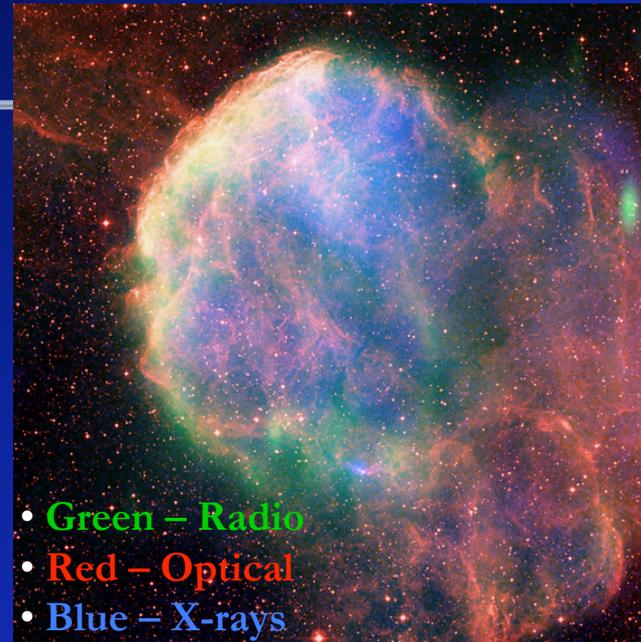
- Energy Spectrum
 - Integrate over 0.32° radius centered on emission peak
 - Well fit by a pure power law
 - Index: $2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$
 - Flux (> 1 TeV) $\sim 5\%$ Crab
- Extension of spectrum is consistent within errors with Milagro point at 35 TeV
- Spectrum may favor hadronic origin?



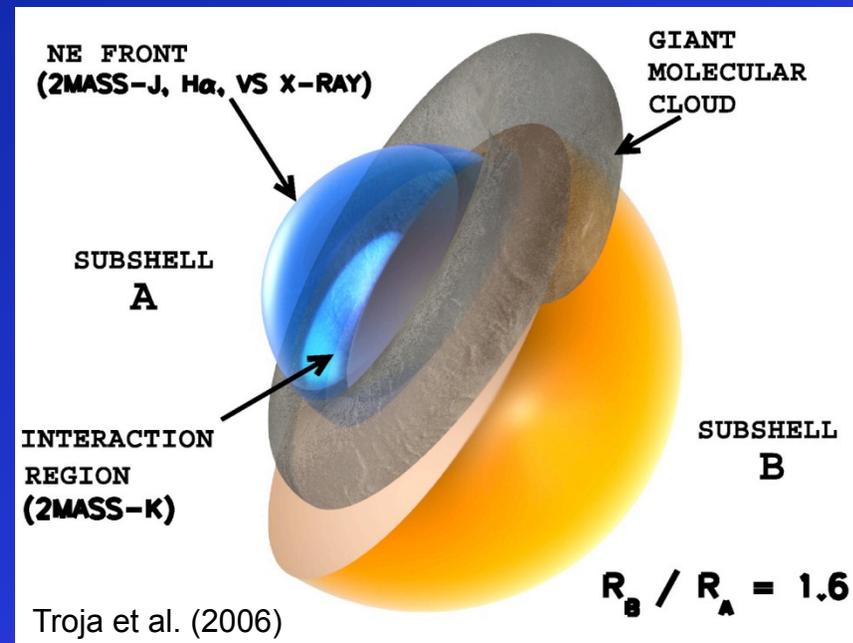
IC 443

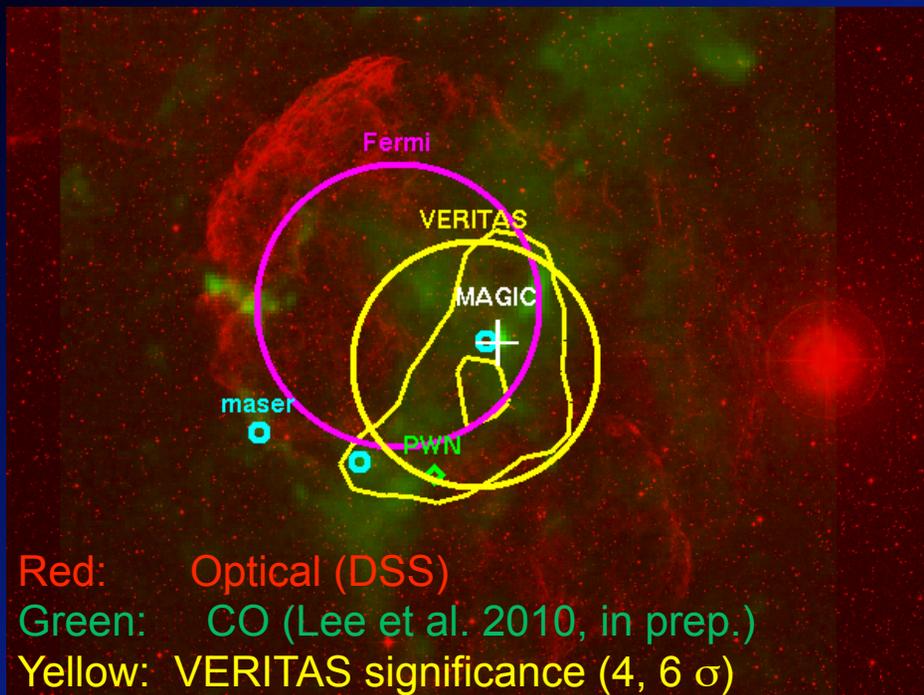
IC 443

- Shell interacting with massive cloud
- Age ~20-30 kyr, 0.75° diameter
- PWN at southern edge of shell
- Discovered in GeV by EGRET
 - Now AGILE, Fermi
- Discovered in TeV in 2007
 - by MAGIC (5.7 σ in 29 hrs)
 - by VERITAS (7.1/6.0 σ pre/post-trials in 15.9 hrs)



- Green – Radio
- Red – Optical
- Blue – X-rays





2-D Gaussian profile fit:

Centroid: $06\ 16.9\ +22\ 32.4\ \pm 0.03_{stat}^{\circ} \pm 0.07_{sys}^{\circ}$
 Extension: $\sigma \sim 0.16^{\circ} \pm 0.03_{stat}^{\circ} \pm 0.04_{sys}^{\circ}$

- ▣ Total live time: 37.9 hrs.
- ▣ 8.3 σ peak significance pre-trials
- ▣ Power-law fit 0.3 – 2 TeV:
 - Index: $2.99 \pm 0.38_{stat} \pm 0.3_{sys}$
 - Flux (> 300 GeV) $\sim 3.2\%$ Crab
- ▣ TeV emission may be
 - CR-induced pion production in cloud
 - associated with the pulsar wind nebula to the south
- ▣ GeV and TeV emission spatially separated? (both extended)
 - Broad-band morphological evolution distinguishes between scenarios (not all PWN)
 - Window into propagation / diffusion of Cosmic Rays in interstellar medium

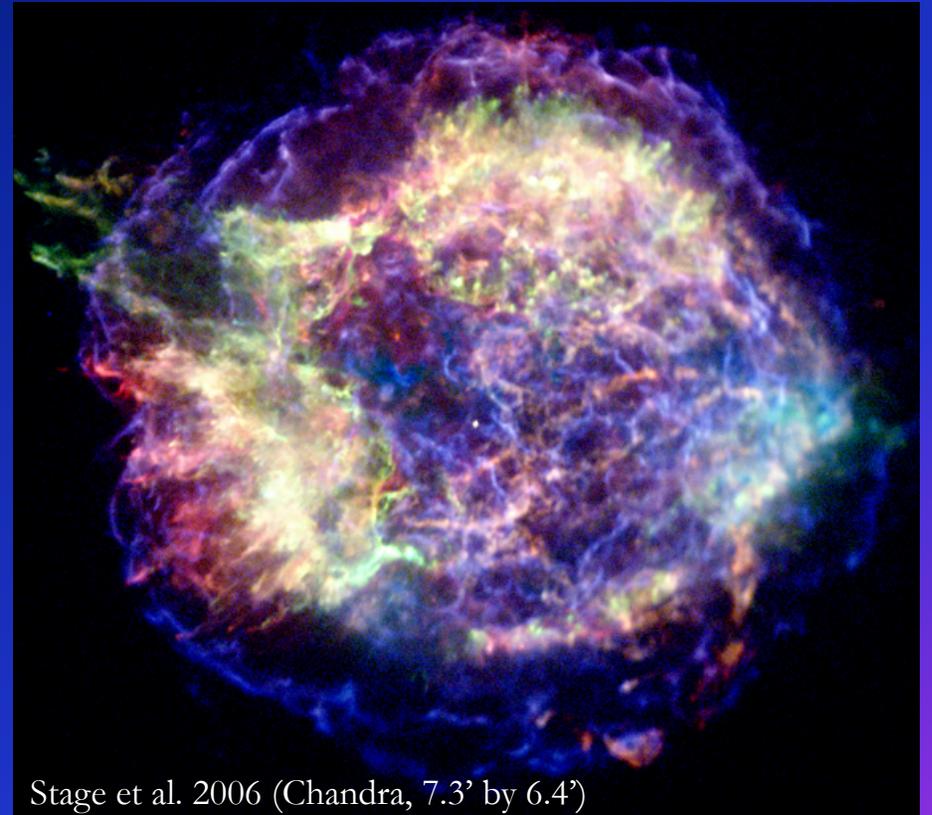
Acciari et al. 2009, ApJ 698 L133

Cassiopeia A

Cassiopeia A



- ▣ Young (~ 330 yr), well studied shell-type SNR
 - Distance ~ 3.4 kpc
- ▣ 5-arcmin diameter
 - Comparable to TeV PSF
- ▣ Discovered in TeV by HEGRA (232 hrs, 5σ), confirmed by MAGIC (47 hrs, 5.3σ)

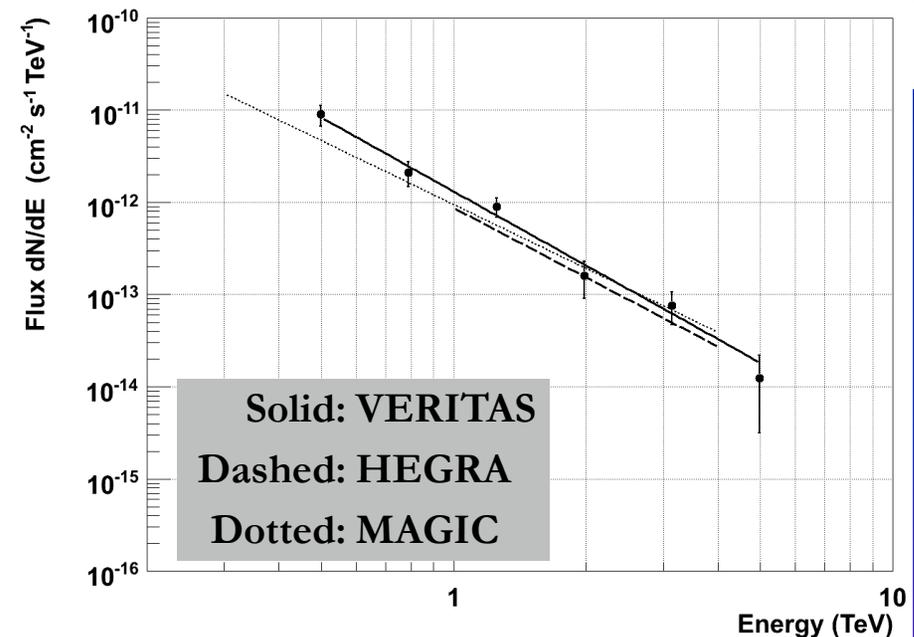
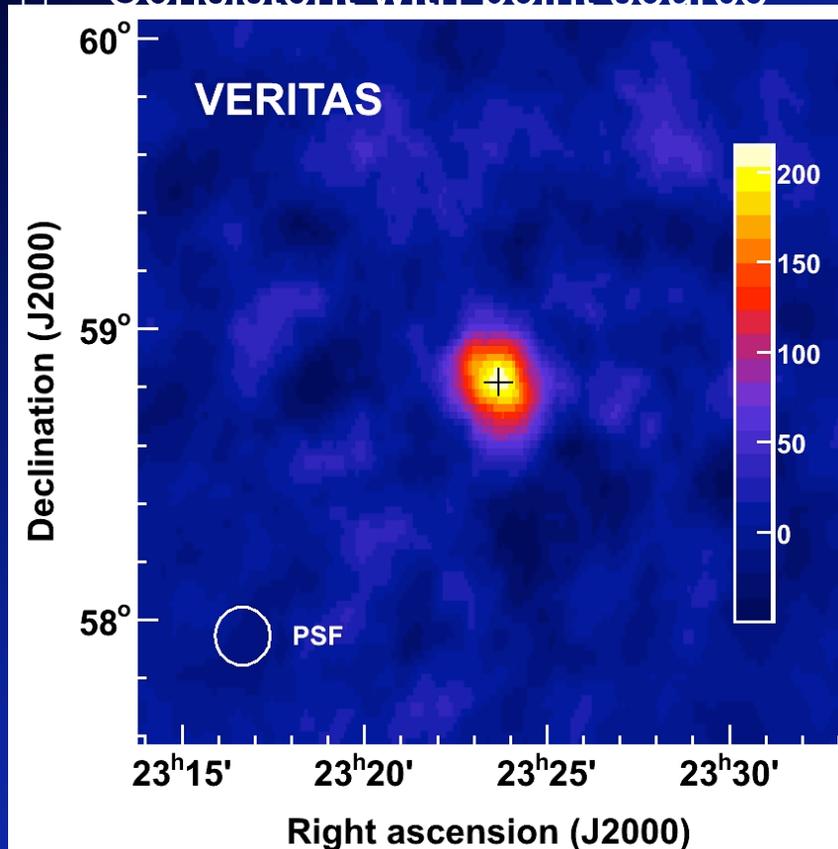


Stage et al. 2006 (Chandra, 7.3' by 6.4')

Cassiopeia A



- VERITAS: 22 hr data in 2007, 8.3 σ
- Consistent with point source



- Index: $2.61 \pm 0.24_{\text{stat}} \pm 0.2_{\text{sys}}$
- Flux (> 1 TeV) $\sim 3.5\%$ Crab
- No sign of a cut-off at high energy.
 - Fermi spectrum connects at lower energy
- Electrons or hadrons?

Acciari et al. 2009, submitted

Summary



- ▣ **SNR G54.1+0.3**: Young TeV PWN with a possible **MC** interaction
 - Detailed MWL modeling will be valuable!

- ▣ **SNR G106.3+2.7**: Extended TeV source – associated with PWN or **SNR/MC** interaction?

- ▣ **IC 443**: Classic SNR / **MC** interaction system
 - Wonderful laboratory to explore cosmic-ray interaction / diffusion

- ▣ **Cassiopeia A**: Young, nonthermal X-ray SNR
 - VHE spectrum is a power law to 5 TeV

- ▣ **See also**
 - *A. Weinstein VERITAS Survey of the Cygnus Region of the Galactic Plane*
 - *E. Aliu VERITAS Observations of Pulsar Wind Nebulae* (poster)

- ▣ **GeV / TeV synergy is only just beginning!**